Preprint: Proc. 2nd CIE Expert Symposium on LED Measurement, May 11-12, 2001, Gaithersburg, Maryland, USA (2001)

Luminous Intensity Measurement of LEDs at NIST

C. Cameron Miller and Yoshi Ohno
[1]National Institute of Standards and Technology, USA

ABSTRACT

Calibration facilities and procedures for measurement of Averaged LED Intensity using the detector-based method have been developed at the National Institute of Standards and Technology (NIST). The scale has been established on two standard photometers calibrated for the required geometries. The current facility utilizes the existing NIST photometric bench and specific LED alignment procedures. The uncertainty of the calibration of the standard photometers as well as for the calibration of LEDs are analyzed in detail. Calibration services are now available for Averaged LED Intensity with a relative expanded uncertainty (*k*=2) ranging from 0.8 % to 3 % (depending on the LED characteristics) and for LED standard photometers for the CIE conditions A and B with an uncertainty of 0.7 % and 0.9 %, respectively.

Keywords: calibration, LED, luminous intensity, Averaged LED Intensity, standard

1. INTRODUCTION

Applications utilizing Light Emitting Diodes (LEDs) are expanding in many areas. As LED applications develop, accurate measurements of LED characteristics become increasingly important. The National Institute of Standards and Technology (NIST) has started a research program to establish appropriate measurement methods and calibration standards for all photometric quantities of LEDs, in particular the luminous intensity of LEDs.

LEDs are unique light sources that differ substantially from traditional lamps in terms of physical size, flux level, spectrum and spatial distribution. The transfer of photometric scales from luminous intensity standard lamps to LEDs is not trivial and large discrepancies of measurement results are reported. One of the major causes of the discrepancies was found to be a large variation in measurement geometries among different laboratories.

To provide a solution to this problem, the International Commission on Illumination (CIE) has introduced a new term, Averaged LED Intensity , which is measured at distances of 316 mm (Condition A) or 100 mm (Condition B) using a photometer having a circular entrance aperture with an area of 100 mm^2 [1]. The new term represents the luminous intensity averaged over the solid angle (0.001 sr or 0.01 sr) defined by these geometries. The calibration of the photometer, however, would require unique procedures and precautions because, at such short distances, the photometers may not follow the inverse square law well due to various near-field effects.

To establish the scale of Averaged LED Intensity at NIST, two standard photometers have been calibrated for the required geometries. A calibration facility and procedures have been developed for the measurement of LEDs utilizing the existing NIST 4 m photometric bench. The uncertainties of these calibrations have been analyzed in detail, and calibration services for Averaged LED Intensity have been established at NIST. This paper discusses the measurement procedures and uncertainty budget for the calibration of the standard photometers as well as for the calibration of LEDs using the detector-based method.

2. CALIBRATION OF LED STANDARD PHOTOMETERS

2.1 Calibration procedures

The Averaged LED Intensity measurement requires a photometer head typically composed of a silicon photodiode, a $V(\lambda)$ correction filter, (a diffuser, optionally), and a circular entrance aperture having an area of 100˚mm^2. A non-diffuser type photometer is often preferred for better spatial uniformity in responsivity within the aperture area and for better rejection of ambient stray light. CIE 127 [1] recommends that the photometer be calibrated by using standard LEDs. At a national laboratory, however, the photometer must first be absolutely calibrated to establish the scale, similarly to the way the luminous intensity unit, the candela, is realized based on standard photometers [2].

For this purpose, NIST uses two temperature-controlled, non-diffuser type standard photometers (hereafter called LED Std photometers) having a 100˚mm^2 circular aperture. These LED Std photometers are calibrated against the NIST standard photometers that hold the NIST illuminance unit [2]. However, the responsivity of the photometer head (normally used and calibrated at ~3˚m) changes slightly when used at such short distances as 100 mm, due to the changes in measurement geometry (increased acceptance angle) causing different interreflection effects within the photometer head. The contribution of error from the position of the photometer reference plane will also be magnified at such short distances. Therefore, appropriate methods should be used to calibrate the LED Std photometers.

To transfer the illuminance scale of the NIST standard photometers to the LED Std photometers, an integrating sphere source (operated at 2856 K) is used as the light source. With the use of a 6˚mm precision aperture in front, this source approximates a point source at distances longer than 0.1 m with negligible errors in using the inverse square law. The luminous intensity of the source is first determined by the NIST standard photometers [2] at a sufficiently long distance (~1 m). The illuminance at 100 mm and 316 mm is calculated based on the inverse square law. Finally, the LED Std photometer is placed so that its reference plane (the front surface of the photometer aperture) is at the exact distance from the sphere source output aperture, and calibrated for illuminance responsivity [A/lx]. Using this method, the results are not affected by any errors in the position of the reference plane of the photometer or the different interreflections within the photometer head. The calibrated responsivity values are valid only at these specific distances.

2.2 Uncertainty Analysis

Table 1 shows the uncertainty budget for the calibration of the NIST LED Std photometers. Many of the components listed are common with those for the calibration of general photometers as described in Ref. [2]. The last two components (geometrical factors and stray light, and alignment of LED Std photometer) are associated specifically with the short photometric distance; they are discussed in detail below. Table 1 does not include the uncertainty of the spectral mismatch correction for LEDs, which is discussed in section 3.

Table 1 —Uncertainty budget for the NIST LED Std Photometers (for CIE Illuminant A).

	Type	Uncertainty (k=2)%
The NIST illuminance unit realization	B	0.39
Long-Term drift of the NIST Std Photometers	B	0.15
Spectral mismatch of NIST Std Photometers for the sphere source	B	0.04
Illuminance nonuniformity	B	0.02
Source stability and random noise	A	0.02
Temperature variation of LED Std photometer	A	0.10
Transimpedance gain of the amplifier	B	0.02
Geometrical factors and stray light	B	0.50
Alignment of LED Std Photometer (0.3 mm in 316 mm)	A	0.20
(0.3 mm in 100 mm)		0.60
Overall Relative Expanded Uncertainty (k=2)	Condition A:	**0.70**
	Condition B:	**0.90**

Geometrical factors and stray light: This component is associated with uncertainties in transferring the illuminance unit at short distances (100 mm and 316 mm). Theoretically, the sphere source with a 6 mm aperture should work as a point source in the distance range from 1 m to 0.1 m. However, our verification measurements using a cosine-corrected photometer with a much smaller precision aperture (3 mm diameter) and precisely measured reference plane (using a microscope with an expanded uncertainty (k=2) of 0.01 mm) showed a few tenths of a percent discrepancy from the inverse square law at distances in that range. The discrepancy was speculated to be due to stray light caused by interreflections between the photometer head and the sphere source but could not be resolved. Therefore, the discrepancy is currently included as a type B uncertainty. This uncertainty component is to be investigated and should be reduced in the future.

Alignment of LED Std photometer: The alignment of the LED Std photometer pertains to the uncertainty of the distance setting for 100 mm and 316 mm, including the reproducibility of the position of the LED Std photometer. In the current NIST facility, this uncertainty is estimated to be 0.3 mm (k=2). This component will also be improved in the future. As mentioned above, the calibration of illuminance responsivity at fixed distances as described above will not be affected by the errors or uncertainties in the position of the reference plane of the photometer. This is a great advantage because the position of the reference plane of commercial photometers is often not accurately defined.

3. CALIBRATION OF LEDS

3.1 Measurement procedures

The LEDs are calibrated on the NIST 4 m photometry bench [2], using the LED Std photometers described in the previous section. Since the scale comes from the calibrated photometers, this is a detector-based method, similar to the method used to calibrate the luminous intensity of lamps at NIST [2]. An LED under test is mounted at a distance of 100 mm or 316 mm from the reference plane of the LED Std photometer, with its mechanical axis aligned to coincide with the photometer axis. See 3.2 for the details of the alignment. The LED is operated at a constant current, and allowed to stabilize (typically 5 min). Then the LED Std Photometer signal is recorded together with the LED electrical parameters. From the photometer signal, the illuminance is calculated and the Averaged LED Intensity is obtained from the measured illuminance and the distance. The measurement is repeated three times including re-alignment of the test LED, to assess the repeatability of measurement. Since some LEDs are fairly sensitive to temperature, the LED ambient temperature is monitored and kept at 25¡C –1¡C during calibration.

3.2 Uncertainty analysis

Presented in Table 2 is the uncertainty budget for calibration of an LED. Starting with the uncertainty of the LED Std photometer calibration, many uncertainty components associated with characteristics of test LEDs must be added. Among them, spectral mismatch correction and alignment of the LED mechanical axis are significant factors. These components are further discussed below.

Spectral mismatch correction factor: An important aspect of the detector-based method of LED intensity measurement is the ability to calculate the spectral mismatch correction factor, F^*, using the relative spectral responsivity of the LED Std photometer, $s(\lambda)$, and the spectrum of the LED, $S_{\mathrm{LED}}(\lambda)$. Uncertainty components involved in the calculation of the F^* are shown in Table 3.

The first component is the spatial nonuniformity of the LED Std photometer response over the entrance aperture, which is wavelength-dependent. The photometer response was mapped with a 1 mm monochromatic beam to determine the spatial nonuniformity at several different wavelengths, and corrections are made to the $s(\lambda)$ measured at the center of the aperture. The values shown in the table are the residual uncertainties after correction. The second component is the uncertainty associated with the bandpass (4 nm) of the

Table 2 —Uncertainty budget for Averaged LED Intensity calibration at NIST.

Components	Type	Rel. exp. uncertainty (k=2) %	
		Cond. A	Cond. B
Calibration of NIST LED Std Photometers	B	0.70	0.90
Long-Term drift of the NIST LED Std Photometers	B	0.15	
Photometer temperature variation	A	0.03	
Spectral mismatch of NIST LED Std Photometer	B	0.08 — 0.62	
LED-to-Photometer distance	B	0.20	0.60
LED current regulation	A	0.02	
Stray light and geometrical aspects	A	0.05	0.10
Transimpedance gain of the amplifier	A	0.02	
Alignment of the LED mechanical axis	B	0.20 — 3.00	
Repeatability of test LEDs	B	0.24 — 0.70	
Ambient Temperature (–1¡C)	A	0.02 — 1.0	
Overall uncertainty of calibration		**0.81 — 3.0**	**1.15 — 3.0**

Table 3 —Uncertainty components in the spectral mismatch correction factor.

Components	Relative expanded uncertainty (k=2) %				
	Blue	Green	Red	Yellow	White
Spatial nonuniformity in $s(\lambda)$	0.25	0.02	0.15	0.05	0.00
Bandpass correction factor (– 1 nm)	0.08	0.02	0.08	0.02	0.00
Type A uncertainty in $s(\lambda)$	0.06	0.05	0.07	0.06	0.01
Type B uncertainty in $s(\lambda)$	0.10	0.05	0.08	0.02	0.02
λ uncertainty (0.1 nm) in $s(\lambda)$	0.53	0.22	0.29	0.11	0.08
λ uncertainty (0.3 nm) in LED spectra, $S_{\mathrm{LED}}(\lambda)$	0.12	0.00	0.09	0.01	0.02
Calculation uncertainty	0.09	0.03	0.14	0.02	0.01
Overall uncertainty in F^*	0.62	0.23	0.39	0.14	0.09

monochromator for the spectral responsivity measurement. Without correction, ~0.3 % error would be seen for the blue and red LEDs. The values shown in the table are the residual uncertainties after correction of $s(\lambda)$ by an approximate deconvolution process. The Type A uncertainty in $s(\lambda)$ is calculated from the standard deviation of the $s(\lambda)$ measurement using the numerical method [4]. The Type B uncertainty is calculated by modeling a systematic error in the measurement.

Another important aspect is the wavelength uncertainty in the spectral response data. Only a 0.1 nm shift of the wavelength scale can cause an error of 0.5 % for blue and red LEDs whose emission peak is at the steep slope of the $V(\lambda)$ curve. This is probably the most critical aspect of the spectral mismatch correction. The uncertainty in the measurement of the spectrum of the test LED is not as critical as the spectral responsivity of the LED Std photometer.

LED alignment: The alignment of LEDs is a major uncertainty component for Averaged LED Intensity measurement. For standard LEDs, one method of alignment is permanently mounting an LED in a fixture that has a reference surface. The distance from the tip of the LED to the reference surface can be measured accurately. The angular alignment will not change because the reference surface will align the LED with the instrument.

Typically, LEDs are not mounted in such a permanent fixture. CIE 127 recommends aligning bare LEDs along their mechanical axis rather than the optical axis (peak of the beam), mainly to achieve uniformity among different laboratories and because it can be done quickly. Two different methods of aligning bare LEDs were tested at NIST, one using a mount that physically holds the LED by the sides of the lens and another that uses a telescope to optically align the LED.

A mount that physically holds the sides can reproducibly place an LED in and out of a holder such that the measurement distance is well known. The LED is easily centered along the detector axis, and can be easily switched from one to another. However, we found it difficult to reproducibly mount the bare LED in the fixture. The fixture relied on placing pressure on the sides of the LED, which caused the sides of the LEDs to become scratched and damaged. In addition, a new fixture had to be fabricated for each different style or size of LED.

A better method is aligning the bare LEDs optically. Using a fixed telescope, a reference point in space is defined along the LED Std photometer axis. The photometer is mounted on the photometric bench with an optical encoder. The reference plane of the LED Std photometer is first moved to the reference point and then translated to the appropriate distance. The bare LED is then mounted on the bench using an adjustable mount that has five degrees of freedom. By viewing the LED from the side telescope, the tip of the LED is translated to the reference point in space, set parallel to the LED Std photometer axis and adjusted vertically. The LED is then rotated 90 degrees on the horizontal plane, adjusted so that it is perpendicular to the LED Std photometer axis, and centered in the horizontal plane. With this procedure, the alignment uncertainty was reduced by a factor of five, though it takes much longer than using a fixture.

4. CONCLUSION

NIST has established the facilities and procedures for calibrating the Averaged LED Intensity using the detector-based method. The calibration services are now available for Averaged LED Intensity with an uncertainty (k=2) of 0.8 % to 3 % (depending on the LED characteristics) and for LED standard photometers for CIE conditions A and B with an uncertainty of 0.7 % and 0.9˚%, respectively. Further work is in progress at NIST to develop dedicated facilities for LED measurements with reduced uncertainties.

REFERENCES

[1] Commission Internationale de l' clairage: Measurement of LEDs, CIE 127-1997.

[2] Ohno Y, NIST Measurement Services: Photometric Calibrations, NIST Spec. Publ. 250-37 (1997).

[3] Larason TC, Bruce SS, and Parr AC, NIST Measurement Services: Spectroradiometric Detector Measurements, Part-I — Ultraviolet detectors and Part-II-Visible to Near Infrared Detectors, NIST Spec. Publ. 250-41 (1998).

[4] OHNO Y, A Numerical Method for Color Uncertainty, Proc. CIE Expert Symposium 2001 on Uncertainty Evaluation, Jan. 2001, Vienna, Austria, 8-11 (2001).

AUTHORS: C. Cameron Miller and Yoshi Ohno, NIST, Stop 8442, 100 Bureau Drive, Gaithersburg MD 20899 USA, Fax: 301-840-8551, E-mail: c.miller@nist.gov, ohno@nist.gov